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CARBON DIOXIDE WASHOUT OF AN EMERGENCY BREATHING SYSTEM MASK MODIFIED FOR USE IN THE ADVANCED SEAL DELIVERY SYSTEM (ASDS) TRAINER

NAVSEA
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Navy Experimental Diving Unit

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A modified Emergency Breathing System full face mask was evaluated for use in the Advanced SEAL Delivery System trainer. The mask contained an oral-nasal cup and two spiral-wound plastic hoses on its inhalation and exhalation openings. Each hose was six feet long with an inside diameter of 1.25 inches and had six rectangular slots cut through the hose wall. The slots were approximately eight inches from one end of each hose. Testing was conducted in an unpressurized hyperbaric chamber that was well ventilated with air. Carbon dioxide (CO_2) washout volume – averaged inspired CO_2 – was calculated at a respiratory minute ventilation of 22.5 liters per minute ($l \cdot min^{-1}$). The mask was ventilated with a mechanical breathing simulator. One hundred per cent CO_2 was injected at 0.9 $l \cdot min^{-1}$ into the breathing loop. Mean CO_2 washout was determined for two configurations: normal, with both hoses positioned so that the slotted ends are near the mask; and reversed exhaust, with inhalation hose positioned with its slots near the mask and exhalation hose positioned with the slots away from the mask. By our normalizing for the actual end-tidal CO_2 level, the volume-averaged CO_2 in the normal configuration was 0.71% and 0.75% with the exhaust reversed. Carbon dioxide washout of the modified emergency breathing system mask with exhaust hose in either configuration is acceptable for use in the ASDS trainer.

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INTRODUCTION

Navy Experimental Diving Unit (NEDU) was tasked by Naval Sea Systems Command (NAVSEA) to test and evaluate the ventilatory sufficiency of a modified Emergency Breathing System (EBS) full face mask (Biomarine Inc; Exton, PA) for use in the Advanced SEAL Delivery System (ASDS) trainer.[1] The evaluation was conducted on behalf of Naval Air Systems Command (NAVAIR), Training Division, Orlando, FL.

In the ASDS during an actual emergency, a SEAL dons an EBS mask and breathes gas through two six-foot long hoses — one for inhalation and one for exhalation — connected to a manifold. Since the ASDS trainer does not have a breathing gas manifold, the original hoses are replaced with spiral-wound plastic hoses through which slots have been cut to allow the wearer to inhale from and exhale into the ASDS trainer compartment. The compartment is not pressurized and is well ventilated by an open loop air conditioning system that does not recycle the compartment atmosphere. The goal of the current study was to determine whether a SEAL wearing the modified EBS full face mask inspires safe concentrations of carbon dioxide (CO_2) during ASDS training. The mask's effect on inspired CO_2 was determined by measuring CO_2 washout — the volume-averaged inspired CO_2 — under conditions approximating those of training.

METHODS

EQUIPMENT AND INSTRUMENTATION

Test equipment was set up as shown in Figure 1. One ASDS trainer mask provided to NEDU by NAVAIR, Training Division, Orlando, FL, contained an oral-nasal cup and was modified by installing two spiral-wound plastic hoses to the mask's inhalation and exhalation openings to simulate the supply and exhaust hoses used inside the ASDS. Each hose was six feet long, with an inside diameter of 1.25 inches. Both hoses had six rectangular slots (approximately 1 inch x ⅜ inch) cut through the hose wall to allow chamber atmosphere to enter and exit during respiration. These slots were located approximately eight inches from one end of each hose and were protected from debris entry by coarse weave screen wire. The slots in the inhalation hose were always positioned 180 degrees from those in the exhalation hose.

PROCEDURES

<u>Testing Conditions</u>. Testing was conducted in an unpressurized hyperbaric chamber while well ventilated with air at ambient temperature (approximately 75 °F). The chamber had an internal volume of 420 cubic feet. The mask was positioned on a manikin head (Figure 2). Ventilation through the mask was achieved by attaching the head to a breathing simulator, a mechanically driven piston within a cylinder.

Carbon Dioxide Washout. CO_2 washout — volume-averaged inspired partial pressure carbon dioxide (P_{CO_2}) in kilopascals (kPa) — and estimated dead space volume (liters) were calculated at a respiratory minute ventilation (RMV) of 22.5 liters per minute ($l \cdot min^{-1}$) — i.e., 1.5 $l \cdot breath^{-1}$ at 15 $breaths \cdot min^{-1}$.[3] The mask was ventilated with air as the medium in a mechanical breathing simulator (Reimers Consulting; Springfield, VA). Gas continuously drawn from the manikin's mouth within the oral-nasal mask was analyzed for CO_2 with an infrared absorption analyzer (Model CD-3A with a P-61B sensor and vacuum pump; Applied Electrochemistry Ametek; Pittsburgh, PA) shown in Figure 3. The delay time between the CO_2 and volume signals was determined after all data were collected. Tidal volume (liters) was determined from the breathing simulator volume signal. One hundred per cent CO_2 controlled by a mass-flow controller (Model 8274; Matheson Tri-Gas, Inc.; Montgomeryville, PA) was injected at 0.9 $l \cdot min^{-1}$ (four percent of RMV) into the breathing loop.

Dead space and the average inspired CO_2 were estimated by the method of Warkander and Lundgren.[3] The amount of inspired CO_2 (A_{CO_2}) — for example, $kPa \cdot liter^{-1}$ — was determined by using the equation

$$A_{CO_2} = \int P_{CO_2} \cdot dV, \qquad \text{(Eq. 1)}$$

where P_{CO_2} is the CO_2 partial pressure at the mouth. For computational reasons, the following equation was used:

$$A_{CO_2} = \Sigma\, P_{CO_2} \cdot \Delta V. \qquad \text{(Eq. 2)}$$

The dead space (V_d) was calculated with the equation

$$V_d = A_{CO_2}/P_{ET}CO_2, \qquad \text{(Eq. 3)}$$

where $P_{ET}CO_2$ is the CO_2 level at the end of the expiration. The average inspired CO_2 ($P_{in}CO_2$) was calculated by using the equation

$$P_{in}CO_2 = A_{CO_2} / V_T, \qquad \text{(Eq. 4)}$$

where V_T is tidal volume.

Additional equipment used

1. Facility data acquisition system
2. CO_2 flow transducer (Model 8272-0453; Matheson Tri-Gas, Inc.; Montgomeryville, PA)
3. Digital temperature standard (Model HH42; Omega Engineering, Inc.; Stamford, CT)
4. Calibration gases with certification:
    a. 2.49% CO_2, balance N_2
    b. 4.97% CO_2, balance N_2

c. 100% CO_2

5. ±1.0 psi oral pressure transducer (Model 289-540-001; Keller; Newport News, VA)

EXPERIMENTAL DESIGN AND ANALYSIS

Mean CO_2 washout and dead space volume were determined during five one-minute breathing periods (15 breaths) for two configurations of the exhaust hoses. The end of each hose distal to the mask was plugged and positioned approximately one foot in front and one foot above its connection to the mask.

1. Normal configuration: both hoses were positioned so that their ends with slots were near the mask.
2. Reversed exhaust: the inhalation hose was positioned with its slots near the mask, while the end of exhalation hose with the slots was positioned away from the mask.

Raw CO_2 measurements were normalized to end-tidal CO_2 = 5% by multiplying CO_2 data by the ratio of the actual end-tidal CO_2 concentration (%) divided by 5%.

RESULTS

CO_2 washout data are presented in Figures 4 through 7. For the normal hose configuration, gas sampling delay time allowed correct determination of volume-averaged inspired CO_2 and dead space volume for only two of five trials. All five trials for the reversed exhaust hose configuration could be used to determine CO_2 ventilation sufficiency. Raw volume-averaged inspired CO_2 levels were approximately 1.2%, with the end-tidal $CO_2 \approx 7\%$ (Figures 4 and 5). The normalized volume-averaged inspired P_{CO_2} (mean ± standard deviation) levels were 0.47 ± 0.04 kPa in the normal hose configuration and 0.76 ± 0.11 kPa in the reversed (Table 1; Figures 6 and 7). The dead space of the mask, regardless of hose configuration, was estimated to be slightly less than 0.2 liter (Table 2).

DISCUSSION

The calculated dead space and CO_2 washout of the modified EBS mask are similar to the dead space of the AGA mask.[3] The AGA mask, like the EBS mask, is approved for use by firefighters.

End-tidal CO_2 normally approximates 5% because of a compensatory change in ventilation to maintain the arterial CO_2 concentration around 40 mm Hg. As a result, the National Institute of Occupational Safety and Health (NIOSH) procedure for determining how a self-contained breathing apparatus affects rebreathing of expired CO_2 requires a relatively complex breathing simulator system to produce the mandated expired gas with 5% CO_2 and inspired gas with no CO_2.[4,5] Although the method used in the present study resulted in the raw volume-averaged inspiratory and end-tidal CO_2 concentration substantially greater than the accepted NIOSH values, the current method yields valid results by employing a much simpler breathing simulator system and a posttest adjustment of the CO_2 concentrations.

The adjustment of CO_2 concentrations can be explained by considering a snorkel filled with the last part of an exhaled breath. The calculated dead space relates the ratio of inspired amount of CO_2 to the end-tidal CO_2. If the snorkeler were to exhale twice the concentration of CO_2, then the end-tidal CO_2 would double — as would the amount inspired of CO_2. Thus, since the ratio of inspired to end-tidal CO_2 remains constant, it is not very critical what the CO_2 flow actually is. By using the concept of the constancy of the ratio of inspired to end-tidal CO_2, it is possible to calculate the average inspired CO_2 when the end-tidal CO_2 and the dead space are known. Had the CO_2 flow been reduced or the ventilation been increased to achieve 5% end-tidal CO_2 instead of the 7% in the present study, the inspired CO_2 concentration would have been only 5/7 of the raw value — i.e., about 0.9%. By normalizing the CO_2 levels, the mean volume-averaged CO_2 for the two runs with hoses in the normal configuration was 0.47% (Figure 6), and for the five runs with the expiratory hose reversed it was 0.76% (Table 1).

Using time-averaged inspired CO_2 concentration as its basis, NIOSH prescribes service times (maximum periods that the apparatus can be worn) for CO_2 concentrations up to 2.5%. Since the normalized inspired CO_2 concentration was approximately 0.9%, service time for the modified EBS mask should not exceed four hours.[4] Our results indicate that the dead space and performance of this mask, regardless of hose configuration, does not impose significant ventilatory encumbrance on the wearer.

CONCLUSION

Ventilation for the modified EBS mask with exhaust hoses in either prescribed configuration is acceptable for use in the ASDS trainer.

REFERENCES

1. U.S. Naval Sea Systems Command, *Task Assignment 05-08: Evaluation of a Full-Face Mask for the ASDS Trainer,* 11 Aug 2005.

2. R. J. Steckel, *Advanced Seal Delivery System (ASDS) Trainer Mask Evaluation*, NEDU Short Form Unmanned TP 05-08, Navy Experimental Diving Unit, Mar 2005.

3. D. E. Warkander and C. E. G Lundgren, “Dead Space in Breathing Apparatus, Interaction with Ventilation,” *Ergonomics*, Vol. 38 (1995), pp. 1745–1758.

4. Public Health Service, Department of Health and Human Services, “Test for Carbon Dioxide in Inspired Gas: Open- and Closed-Circuit Apparatus; Maximum Allowable Limits,” *Code of Federal Regulations*, Title 42, Sec. 84.97 (Washington, DC: U.S. Government Printing Office, 2004), p. 525.

5. E. J. Kloos and J. A. Lamonica, *A Machine-Test for Measuring Carbon Dioxide in the Inspired Air of Self-Contained Breathing Apparatus*, United States Department of the Interior, Bureau of Mines, Report 6865, 1966.

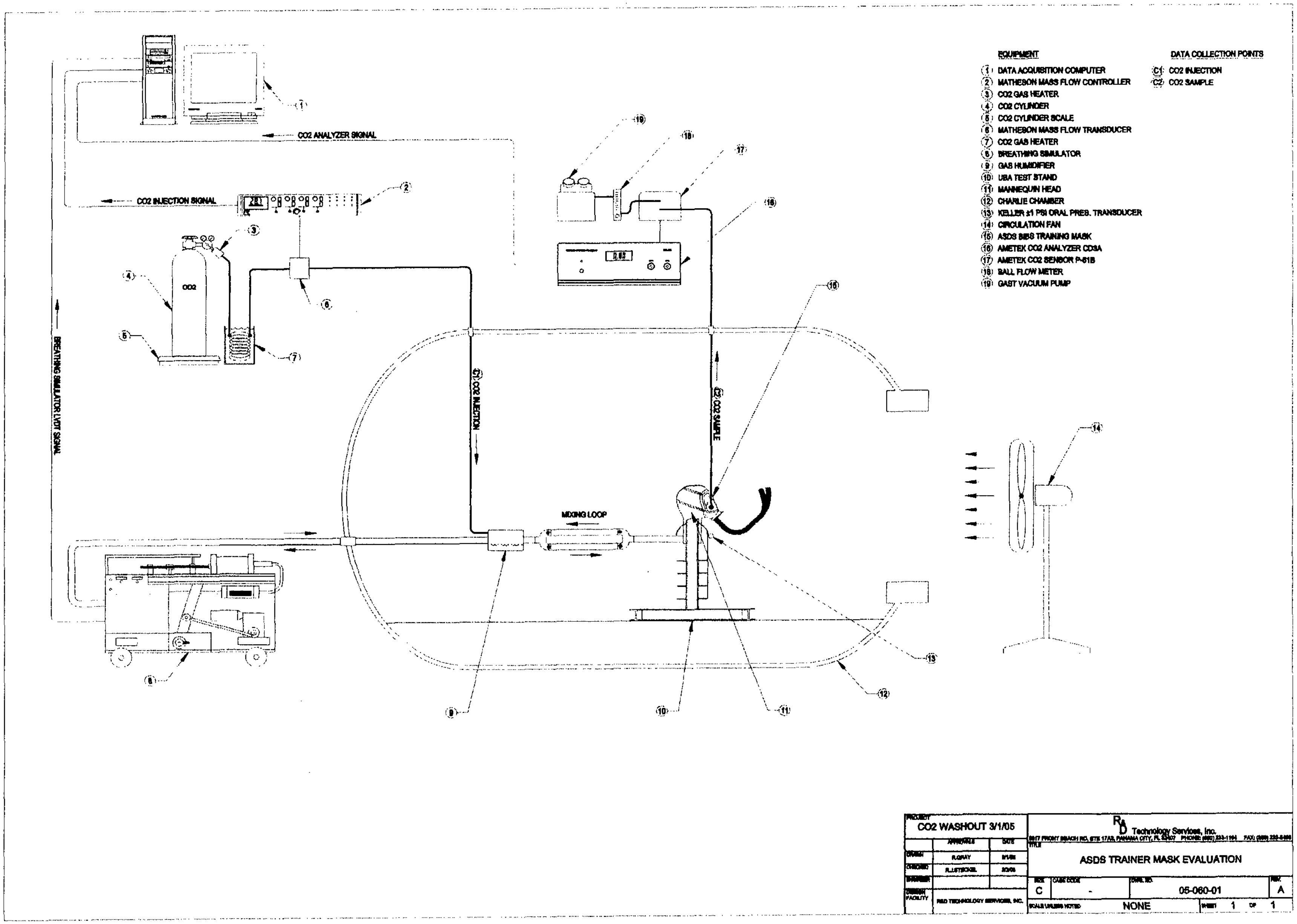

Figure 1. Test Equipment.

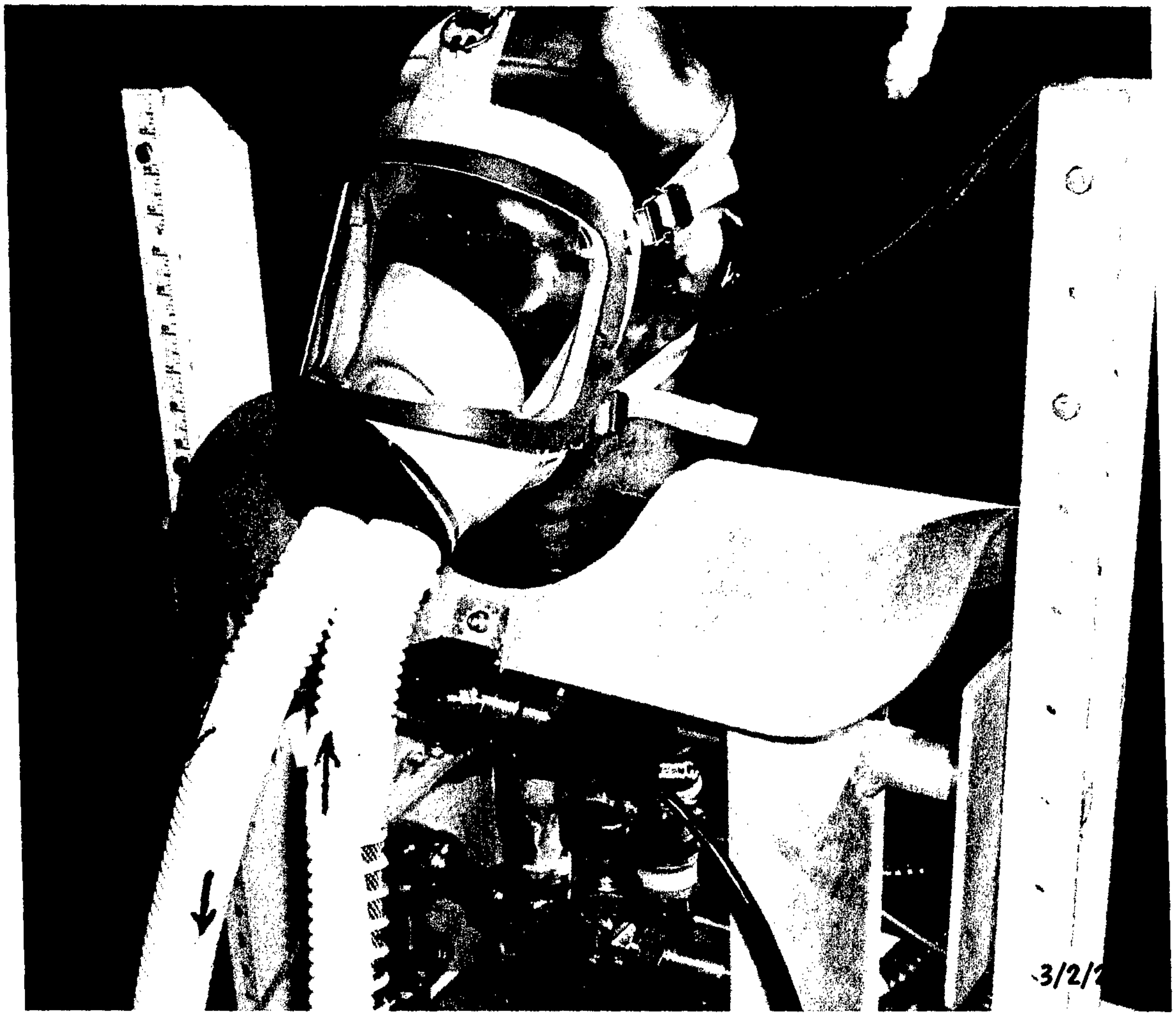

Figure 2. ASDS trainer mask positioned on a manikin head. Stainless steel pipes pass through the head and form an airway from the mouth inside the oral-nasal mask to the breathing simulator. Arrows indicate the direction of the gas flow. Slots cut through the inhalation hose are visible.

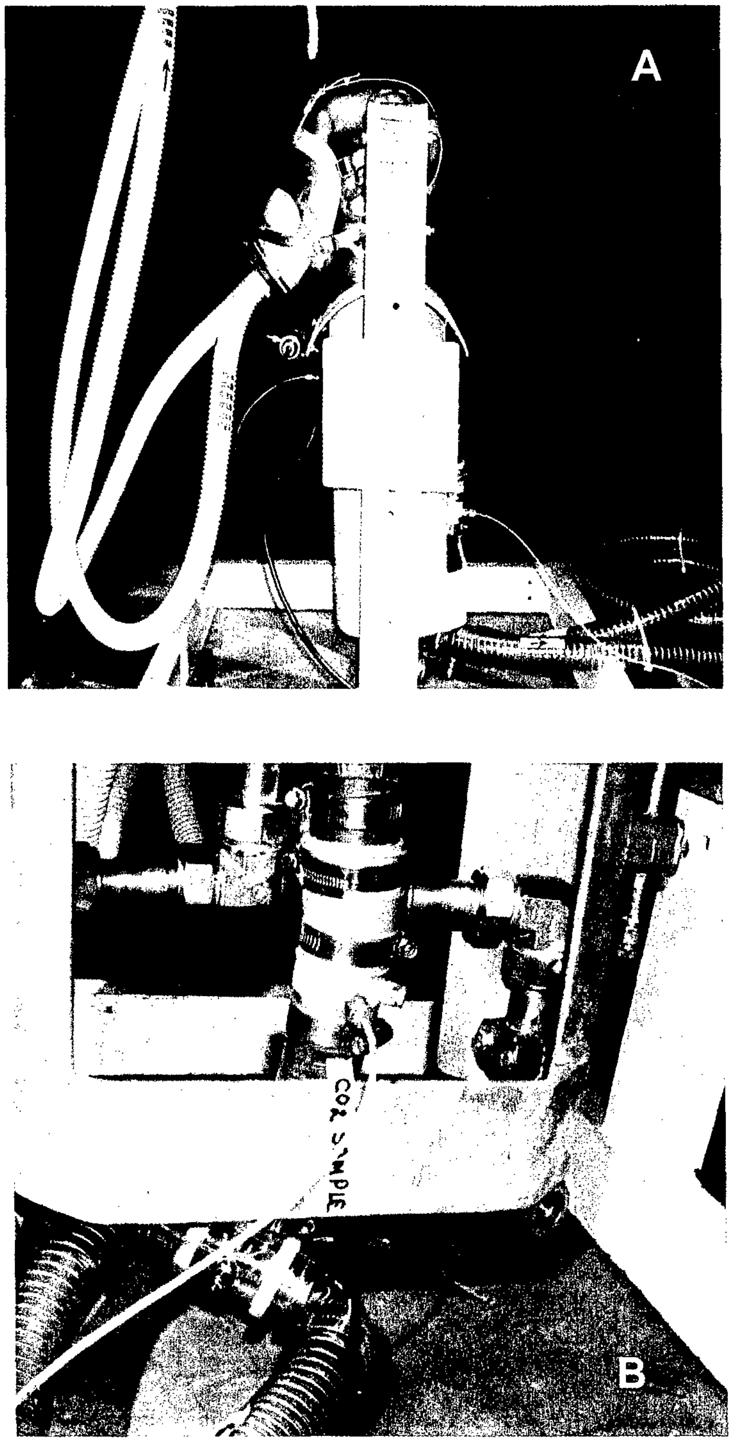

Figure 3. (a) ASDS trainer mask positioned on a manikin head. Slots cut through hoses are visible. (b) The gas sampling line enters the airway piping through a fitting at the rear and is threaded up to the mouth.

Table 1.
Normalized volume-averaged inspired CO_2 (kPa) for both mask configurations.

Mask-hose configuration	**Volume-averaged inspired P_{CO_2} (kPa)**						
Trial	1	2	3	4	5	mean	SD
Normal	---	---	---	0.50	0.43	0.47	0.04
Reversed	0.64	0.75	0.73	0.94	0.72	0.76	0.11

Table 2.
Calculated dead space volume (liters) for both mask configurations.

Mask-hose configuration	**Dead Space (l)**						
Trial	1	2	3	4	5	mean	SD
Normal	---	---	---	0.15	0.13	0.14	0.01
Reversed	0.18	0.18	0.18	0.18	0.18	0.18	0.00

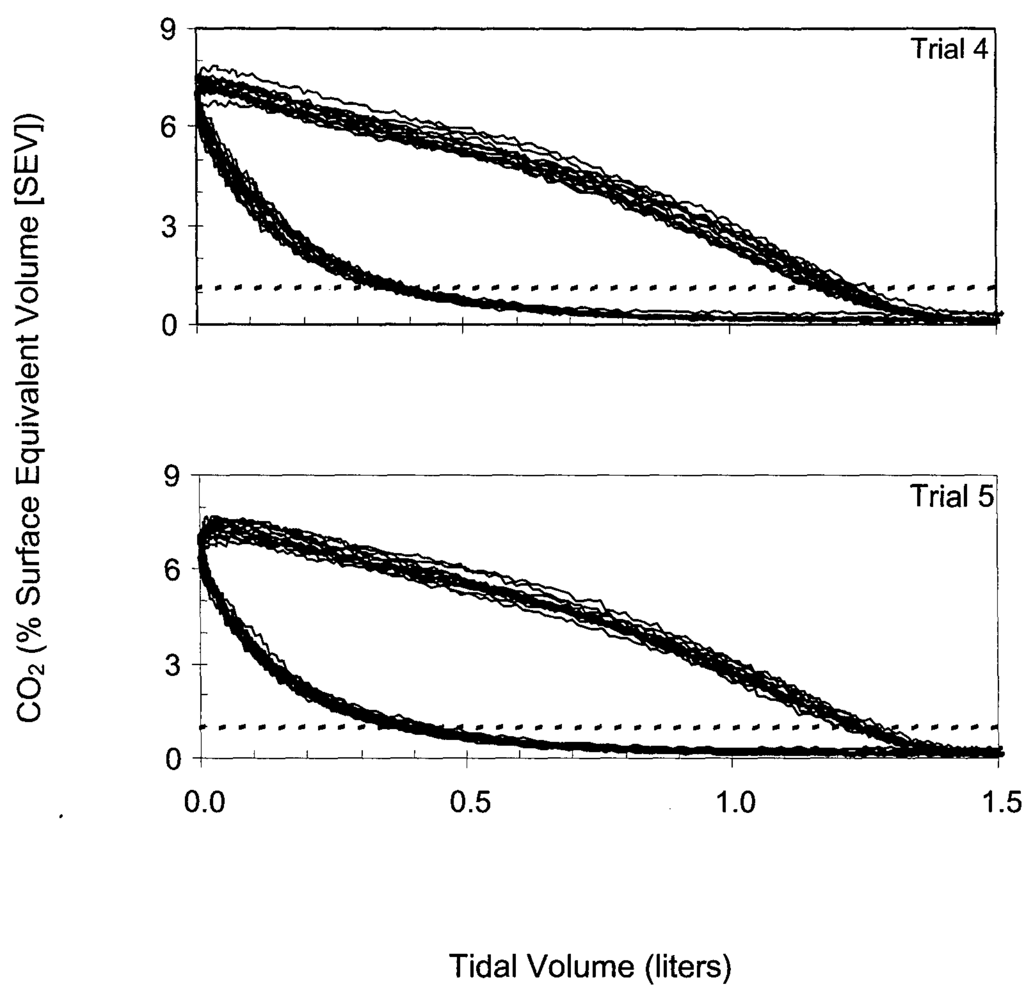

Figure 4. Raw volume-averaged inspired CO_2 of the modified EBS mask when the slots in both hoses are near the mask. The dotted line in each panel indicates the average inspired level of CO_2.

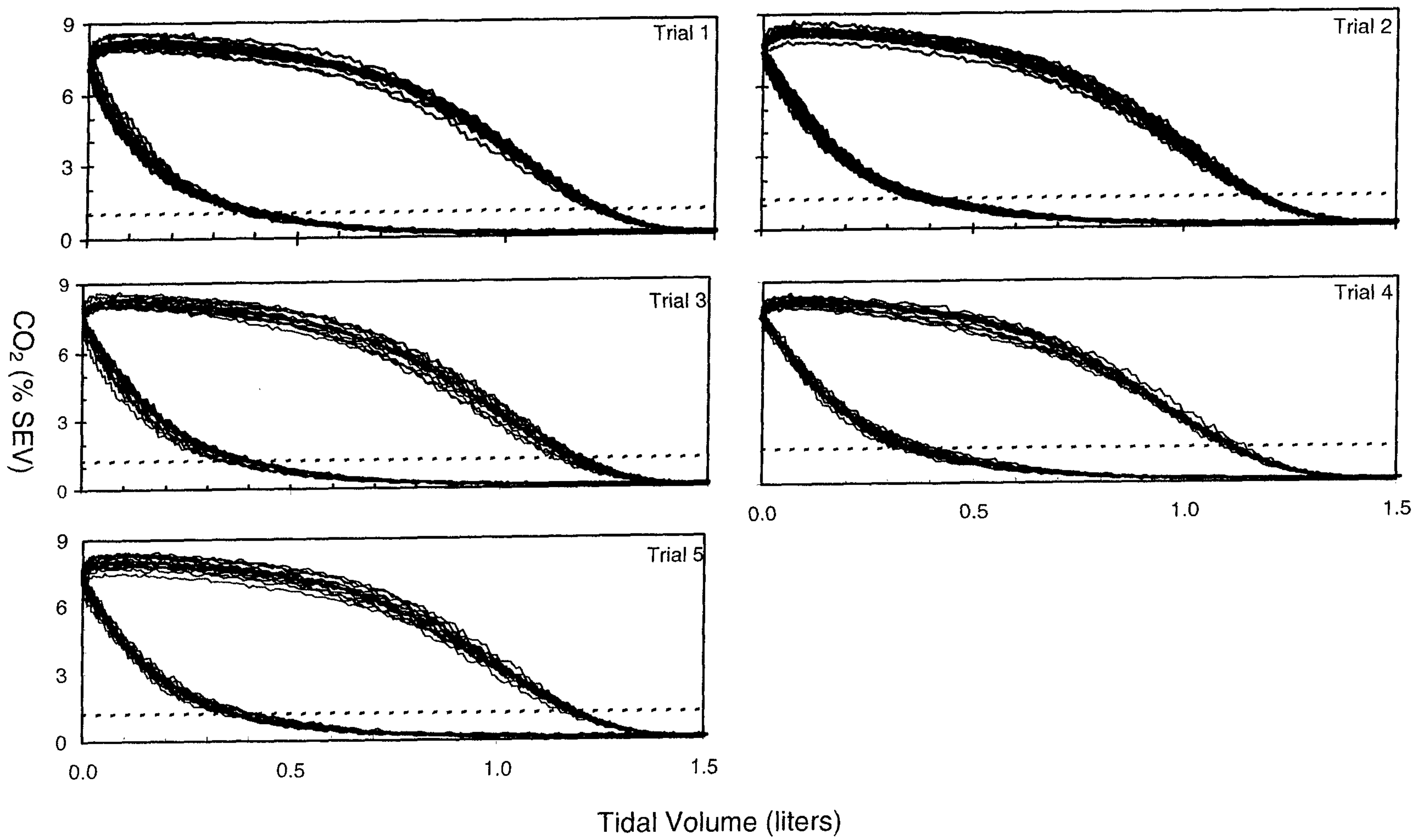

Figure 5. Raw volume-averaged inspired CO_2 of the modified EBS mask when the slots in the inhalation hose are near the mask and those in the exhalation hose are positioned away from the mask. The dotted line in each panel indicates the average inspired level of CO_2.

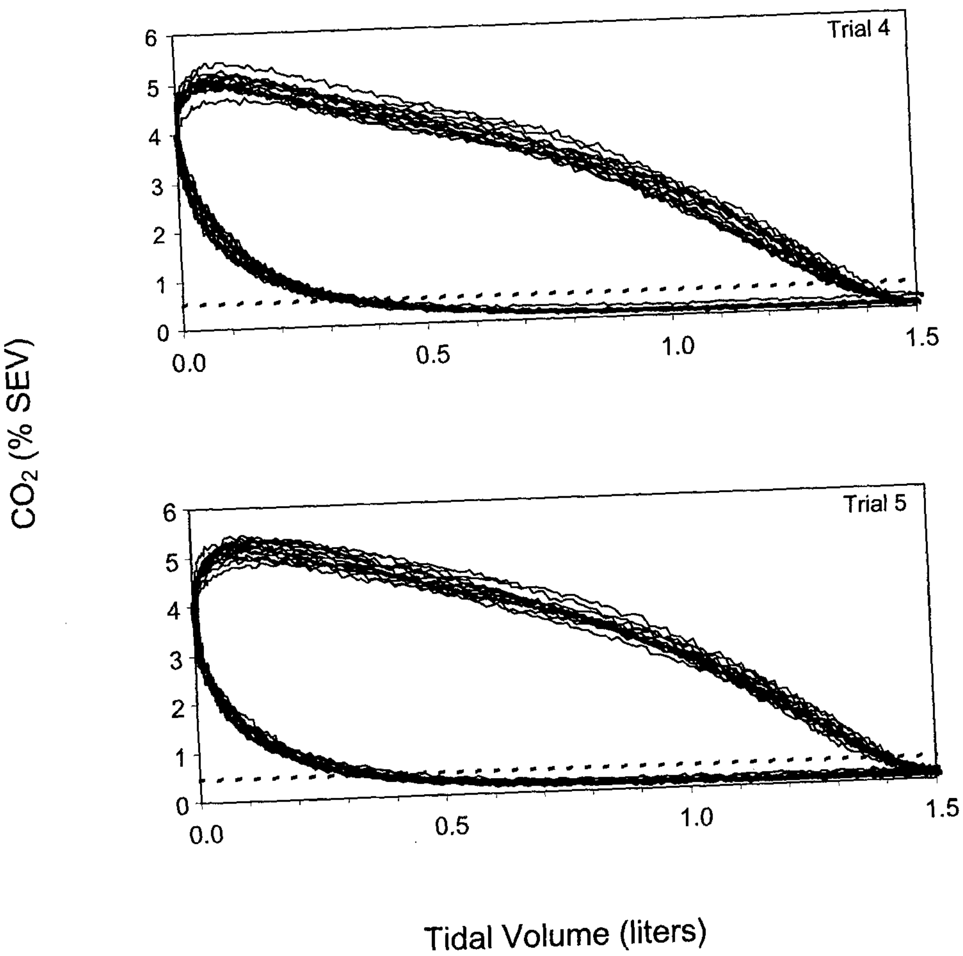

Figure 6. Normalized volume-averaged inspired CO_2 of the modified EBS mask when the slots in both hoses are near the mask. The dotted line in each panel indicates the average inspired level of CO_2.

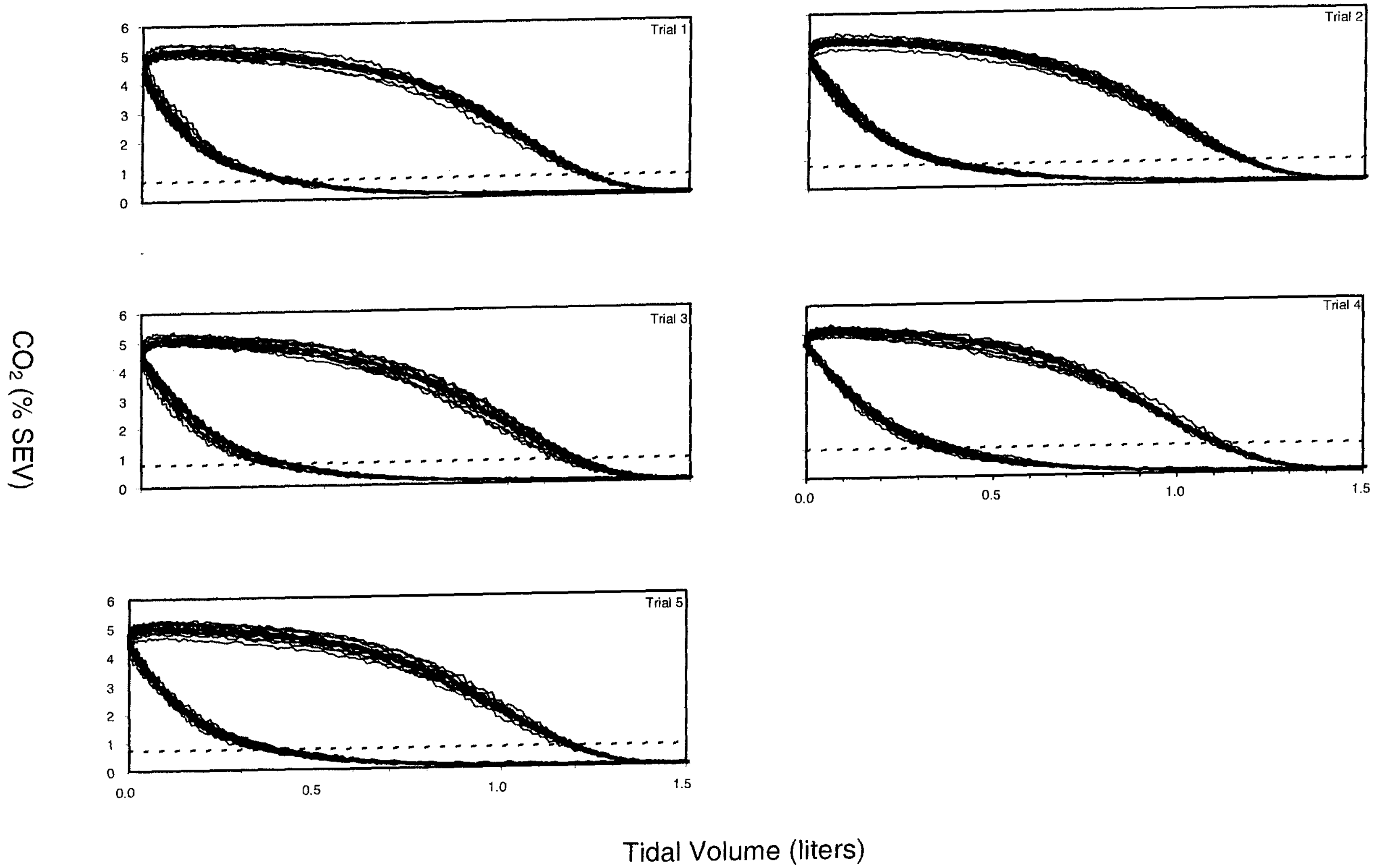

Figure 7. Normalized volume-averaged inspired CO_2 of the modified EBS mask when the slots in the inhalation hose are near the mask and those in the exhalation hose are positioned away from the mask. The dotted line in each panel indicates the average inspired level of CO_2.